THE DISTRIBUTION OF GALACTIC 511 keV POSITRON ANNIHILATION RADIATION

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ABSTRACT

The Oriented Scintillation Spectrometer Experiment (OSSE) on NASA's *Compton Gamma-Ray Observatory* has completed numerous observations of the Galactic plane and Galactic center region. A principle objective of these observations was to measure the distribution of the Galactic positron annihilation radiation. Most of these observations provided positive detections of the narrow 511 keV annihilation line. These data were fitted using several diffuse distribution models representing various populations of progenitor objects. The only model investigated which is not rejected is a two-component distribution consisting of spheroidal and disk components; all other models investigated can be rejected at the $> 4.5\sigma$ confidence level. The size of the spheroidal component is found to be < 500 pc; the disk component of the distribution is not well constrained by the current observations. Adding a point source of emission at the location of the black hole candidate 1E 1740.7–2942 does not significantly improve the model fits. There is no evidence for significant time variability of the 511 keV line flux during observations of the Galactic center region. When compared to historical observations of the Galactic center region by other instruments, the two-component diffuse model suggests a limit to a time-variable component of the 511 keV line flux of $\sim 4 \times 10^{-4}$ γ cm^{-2} s^{-1}.

INTRODUCTION

Numerous observations of positron annihilation from the direction of the Galactic center have been performed over the past 20 years (see Purcell *et al.* 1993; Lingenfelter & Ramaty 1989a and references therein). These observations have utilized various types of detectors and have included both satellite and balloon-borne instruments. Nearly all of these observations have resulted in positive detections of a 511 keV line characteristic of positron annihilation. The line centroid and width have been measured using high resolution Ge-based detectors. The line is found to be within ~ 0.5 keV of 511 keV and to have a full-width at half-maximum (FWHM) of 2.5 ± 0.4 keV (Leventhal *et al.* 1993). The intensity of the line has been found to be positively

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correlated with the instrument field-of-view, indicating there is a diffuse component to the observed emission (see Teegarden 1994). There have also been reports of time-variability in the 511 keV line flux when the Galactic center region was observed at different times by the same instrument (Riegler *et al.* 1981; Leventhal *et al.* 1982; Leventhal *et al.* 1986), suggesting there is also a point source component to the observed emission.

The diffuse component of the 511 keV line emission could be produced by several different mechanisms (see Lingenfelter & Ramaty 1989b and references therein), including: cosmic-ray interactions in the interstellar medium, gamma-ray bursts, pulsars, and β^+-decay products from radioactive nuclei (*e.g.*, ^{56}Co, ^{44}Sc, and ^{26}Al) produced by supernovae, novae, or Wolf-Rayet stars. Photon-photon pair production in the vicinity of an accreting black hole has been suggested as a possible source of time variable annihilation emission (Ramaty *et al.* 1992).

One candidate for a point source of positrons is the black hole candidate 1E 1740.7–2942. Observations by the SIGMA instrument have identified 1E 1740.7–2942 as an extremely time variable hard x-ray source (Churazov *et al.* 1993a). During an ~ 13 hour period on 1990 October 13–14, the SIGMA instrument observed a strong flare from 1E 1740.7–2942 which exhibited an intense ($\sim 10^{-2} \gamma$ cm^{-2} s^{-1}), broad line feature (FWHM ~ 240 keV) with an energy of ~ 470 keV (Bouchet *et al.* 1991). This feature has been interpreted as a broadened, red-shifted 511 keV line resulting from positron annihilation occurring in an accretion disk surrounding 1E 1740.7–2942 (Sunyaev *et al.* 1991; Ramaty *et al.* 1992). Similar outbursts were observed by SIGMA in 1991 October and 1992 September (Churazov *et al.* 1993b; Cordier *et al.* 1993), though a simultaneous observation of the Galactic center region by the OSSE instrument during the 1992 September outburst did not detect the reported excess (Jung *et al.* 1994). There is no direct evidence, however, that the transient line feature observed by SIGMA is related to the narrow 511 keV line which has been observed since the early 1970's. Further, both the SIGMA and GRIP instruments have provided 95% confidence upper limits of $\sim 4 \times 10^{-4} \gamma$ cm^{-2} s^{-1} for time-averaged narrow 511 keV line emission from 1E 1740.7–2942 (Lei *et al.* 1993, Heindl *et al.* 1993).

The Oriented Scintillation Spectrometer Experiment (OSSE) on NASA's *Compton Gamma-Ray Observatory* (GRO) satellite provides the unique ability to perform high-sensitivity observations of the Galactic plane and Galactic center region to measure the distribution of positron annihilation radiation and to search for time variability of the emission. The OSSE observations of the Galactic plane and Galactic center region collected over the period 1991 July 12 – 1993 September 7 have been used to investigate the distribution of the diffuse 511 keV line emission and to search for possible time variability of the emission. These data are found to be best-fit by a two-component distribution model consisting of disk and spheroidal components. All other distribution models investigated can be excluded at the $> 4.5\sigma$ level. There is no evidence for time-averaged narrow 511 keV line emission from the black hole candidate 1E 1740.7–2942. There is no evidence for significant time variability of the 511 keV line flux. The best-fit distribution model is also compared with previous results by other instruments to place historical limits on the time variability of the 511 keV line emission.

MODEL DISTRIBUTIONS

Several diffuse distribution models were investigated representing various populations of possible progenitor objects. With the exception of the CO Distribution, which is based on Galactic CO observations (Dame *et al.* 1987), the distributions are

based on geometric models for the volume emissivities, ϵ, throughout the Galaxy. For each geometric model, a surface-brightness model was generated on a $1° \times 1°$ grid in Galactic coordinates by numerically integrating the volume emissivity function along each line-of-sight. The integration was confined to a cylinder of radius $R = 20$ kpc and height $h = 15$ kpc, centered on the Galactic center, and used an integration step size of 0.25 kpc and a solar galactocentric radius of $R_\odot = 8.5$ kpc. The surface-brightness models were normalized to the total flux within 0.5 radian of $l = 0°$, $b = 0°$. The form of the volume emissivities for each of the models is described below.

The CO Model, originally described by Leising and Clayton (1985), is based on the results of CO surveys and consists of a radial surface emissivity of the form:

$$\epsilon_{\mathrm{CO}}(\rho, z) = \rho^{7.3} \exp\left(-\frac{|z|}{0.120} - 1.37\rho\right) \tag{1}$$

where ρ is the galactocentric radius and z is the distance out of the Galactic plane, both in units of kpc. The scale height of 120 pc was used based on the observed scale height of interstellar dust and gas in the Galaxy (Mihalas & Binney 1981).

The M31 Nova Model, originally described by Leising and Clayton (1985), is based on the observed radial distribution of novae in M31 and is represented by:

$$\epsilon_{\mathrm{M31}}(\rho, z) = \begin{cases} \exp\left(-\frac{|z|}{0.3}\right) & \rho < 1 \text{ kpc} \\ 6.140 \exp\left(-\frac{|z|}{0.3} - 1.87\rho\right) & 1 \text{ kpc} \leq \rho < 2.4 \text{ kpc} \\ 0.177 \exp\left(-\frac{|z|}{0.3} - 0.37\rho\right) & \rho \geq 2.4 \text{ kpc} \end{cases} \tag{2}$$

The Galactic scale height of 300 pc was assumed based on the observed scale height of novae in the Galaxy (Mihalas & Binney 1981).

The Hot Plasma Model of Skibo et $al.$ (1992), which represents an empirical model for the distribution of hot plasma as traced by the 6.7 keV Fe line, was also used. This model is given by:

$$\epsilon_{\mathrm{HP}}(\rho, z) = \exp\left[-\left(\frac{x}{0.15}\right)^2 - \left(\frac{y\cos(\theta) - z\sin(\theta)}{0.15}\right)^2 - \left(\frac{y\sin(\theta) + z\cos(\theta)}{0.08}\right)^2\right]$$
$$+ 25\left(\frac{\rho}{R_\odot}\right)^5 \exp\left(-\frac{11\rho}{R_\odot} - \frac{|z|}{0.1}\right) \tag{3}$$

The Visual Luminosity Model is based on a model for the total star density in the Galaxy (Bahcall and Soneira 1980), and is given by:

$$\epsilon_{\mathrm{VL}}(\rho, z) = 0.15\epsilon_d(\rho, z) + 0.00019\frac{\epsilon_s(R)}{\epsilon_s(R_\odot)} \tag{4}$$

where $\epsilon_d(\rho, z)$ is the volume emissivity for the disk component and $\epsilon_s(R)$ is the volume emissivity for the spheroidal component at a distance R from the Galactic center. These volume emissivities are given by:

$$\epsilon_d(\rho, z) = \exp\left(-\frac{|z|}{0.25} - \frac{\rho - R_\odot}{3.5}\right) \tag{4a}$$

$$\epsilon_s(R) = \begin{cases} (0.2)^{-7/8} \exp(-7.669(0.2)^{1/4}) & R < \frac{0.2}{3}R_\odot \\ \left(\frac{3R}{R_\odot}\right)^{-7/8} \exp\left[-7.669\left(\frac{3R}{R_\odot}\right)^{1/4}\right] & R \geq \frac{0.2}{3}R_\odot \end{cases} \tag{4b}$$

The Nova Model of Higdon and Fowler (1989) also consists of separate disk and spheroidal components and is given by:

$$\epsilon_{\mathrm{NM}}(\rho, z) = \epsilon_d(\rho, z) + 0.00557\epsilon_s(R) \tag{5}$$

where $\epsilon_d(\rho, z)$ and $\epsilon_s(R)$ are the volume emissivities in the disk and spheroidal components, respectively. These volume emissivities are given by:

$$\epsilon_d(\rho, z) = \exp(-44.5z^2 - 0.297(\rho - R_\odot)) \tag{5a}$$

$$\epsilon_s(R) = \exp\left[10.093\left(1 - (R/R_\odot)^{1/4}\right)\right]$$
$$\times \begin{cases} 1.25(\frac{R}{R_\odot})^{-3/4} & R < 0.03R_\odot \\ (\frac{R}{R_\odot})^{-7/8}(1 - 0.08669(\frac{R}{R_\odot})^{-1/4}) & R \geq 0.03R_\odot \end{cases} \tag{5b}$$

The Free Spheroidal Model was constructed to better characterize the size of the spheroidal component of the distribution. This model is also composed of spheroidal and disk components and is given by:

$$\epsilon_{\mathrm{FS}}(\rho, z) = A_d \times \epsilon_d(\rho, z) + A_s \times \epsilon_s(R) \tag{6}$$

where A_d and A_s are free parameters of the fit representing the amplitudes of the disk and spheroidal components, respectively. The volume emissivities of the disk and spheroidal components for this model are given by:

$$\epsilon_d(\rho, z) = \exp\left(-\frac{|z|}{0.25} - \frac{\rho - R_\odot}{3.5}\right) \tag{6a}$$

$$\epsilon_s(R) = \begin{cases} (\frac{R_{core}}{R_{scale}})^{-7/8} \exp\left[-(\frac{R_{core}}{R_{scale}})^{1/4}\right] & R < R_{core} \\ (\frac{R}{R_{scale}})^{-7/8} \exp\left[-(\frac{R}{R_{scale}})^{1/4}\right] & R \geq R_{core} \end{cases} \tag{6b}$$

Note that equations 6a and 6b have the same form as the spheroid and disk components of the Visual Luminosity Model given in equations 4a and 4b, with the spheroid core size (R_{core}) and scale size (R_{scale}) as additional parameters in equation 6b. For this distribution, models were generated on a grid with various values of the parameters R_{core} and R_{scale}. The values for the parameter R_{core} spanned the range $0.02 - 1.0$ kpc and the values for the parameter R_{scale} spanned the range $0.005 - 2.0$ pc.

In addition to the diffuse models described above, the possibility of a point source of 511 keV line emission in the direction of the Galactic center was also investigated by modeling the response to individual point sources on a $0.1° \times 0.1°$ grid within the range $-5° \leq l \leq 5°$ and $-5° \leq b \leq 5°$. A point source located at the position of the X-ray source 1E 1740.7–2942 ($359.14°$, $-0.09°$) was also investigated separately.

ANALYSIS AND RESULTS

The surface-brightness models described above were used to fit the narrow 511 keV line data. The OSSE data fitted include those reported by Purcell *et al.* (1993) as well as additional data collected during the period 1992 November 17 – 1993
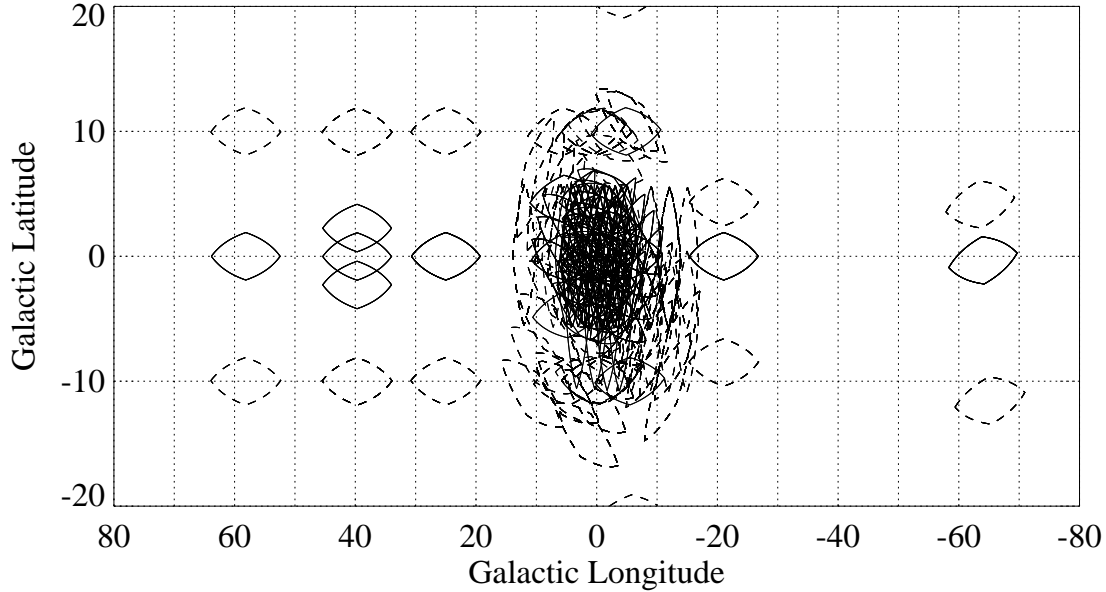
Figure 1: The OSSE fields-of-view for the observations used in the current analysis, shown in Galactic coordinates. The contours represent the 50% response levels for each of the OSSE observations. The fields used as background measurements are indicated by the dashed contours.

September 7. A paper describing the latter data is in preparation (Purcell *et al.* 1994). The OSSE fields-of-view for the observations used in this analysis are shown in Figure 1. The OSSE observations of the Galactic center region show no evidence for significant time-variability of the 511 keV line flux (see Figure 2 and the discussion below), so only time-independent models were investigated. Including the results from several Gamma-Ray Imaging Spectrometer (GRIS) observations of the Galactic plane and Galactic center were also investigated. These additional data included the results of the GRIS observations of the Galactic center in 1992 April/May (Leventhal *et al.* 1993), since they were nearly coincident with one of the OSSE observations of the Galactic center, and the GRIS observation of the Galactic plane ($l = 335°$) in 1988 October (Gehrels *et al.* 1991). The latter was investigated since, because there was little response to the Galactic center region during this observation, it represents a measure of the diffuse component of the emission independent of any potential point source near the Galactic center.

For each separate observation, the response for each normalized surface-brightness model was calculated by convolving the 2-dimensional angular distribution with the corresponding instrument angular response. The OSSE photopeak angular response used for this analysis was based on detailed angular calibrations performed prior to launch (Johnson *et al.* 1993). The GRIS angular response was taken to be (Skibo *et al.* 1992):

$$r(\theta) = \begin{cases} 1 - 0.057\theta & \theta < 16.75° \\ 0.067 - 0.0013\theta & \theta \geq 16.75° \end{cases} \qquad (7)$$

For the OSSE observations, the determination of the model response included the instrument response for the offset-pointed background positions (see the discussion in Purcell *et al.* 1993). For the GRIS observations, it was assumed that the background observations were taken sufficiently far from the Galactic plane that there

Table 1: Free Spheroidal Model Fit Results

Dataset	χ^2	N_{dof}	$P(\chi^2, N_{dof})$	Model Flux[a] Spheroidal[b]	Disk[b]	TOTAL[c]
OSSE	135.97	95	0.004	1.5 ± 1.0	0.5 ± 0.1	2.0 ± 0.9
OSSE + GRIS	136.72	98	0.006	1.7 ± 0.6	0.5 ± 0.1	2.2 ± 0.7

[a] $(\times 10^{-3}\ \gamma\ cm^{-2}\ s^{-1})$ within 0.5 radian of $l = 0°$, $b = 0°$.
[b] Uncertainties represent 1σ confidence range for two parameters $(\chi^2_{min} + 2.3)$.
[c] Uncertainties represent 1σ confidence range for one parameter $(\chi^2_{min} + 1.0)$.

was an insignificant contribution from the source distribution during the background measurements.

The model fluxes were determined by fitting the model responses to the data using weighted linear least-squares fitting techniques (Eadie *et al.* 1971). The covariance matrix used in the fit was generated using the statistical uncertainties in the fitted 511 keV line fluxes and included the appropriate correlation terms between the OSSE scanning observations. These correlations were introduced in the background estimation process where, for a given observation period, the same background measurements were used by multiple source positions. The values of the correlation coefficients typically ranged between -0.08 and 0.27, with a median value of ~ 0.11.

With the exception of the Free Spheroidal Model, all of the models tested can be rejected at a high level of significance ($> 4.5\sigma$). The fitted fluxes for the Free Spheroidal Model components are given in Table 1. Of the models investigated, this model provides the most acceptable fit to the data. The M31 Novae Model provides the next-best fit ($\chi^2 = 173.88$, $P(\chi^2, 98) = 4 \times 10^{-6}$), with all of the remaining models having probabilities $< 10^{-8}$. Including the GRIS observations in the model fits does not reject any additional models, but does provide constraints on the Free Spheroidal Model parameters R_{core} and R_{scale}. The GRIS results were included in the model fits discussed below.

There is no evidence for significant variability of the 511 keV line flux during observations of the Galactic center (see Figure 2); small differences in the observed fluxes can be explained by differences in the observation configuration. For the Free Spheroidal Model, the best-fit values for R_{core} and R_{scale} are 0.3 kpc and 1.2 pc, respectively. The 1σ confidence constraint for the core size is $R_{core} < 0.5$ kpc. The Free Spheroidal Model fit is not improved significantly if the disk component given by Equation 6a is replaced by any of the other disk models investigated, indicating that the disk component of the emission is not significantly constrained by the current observations. The range of fitted fluxes for different disk components is $\sim (3-5) \times 10^{-4}$ $\gamma\ cm^{-2}\ s^{-1}$ within 0.5 radian of $l = 0°$, $b = 0°$.

For the Point Source Grid Model, the best-fit point source position is found to be $l = 0.7° \pm 0.6°$, $b = -0.8° \pm 0.3°$, and is consistent with the Galactic center at the $\sim 3\sigma$ level. The slight offset in the best-fit point source position provides marginal evidence for an asymmetry in the distribution of the 511 keV line emission; however, the asymmetry can not be explained by assuming additional 511 keV line emission from the x-ray source 1E 1740.7–2942. Adding a point source at the location of 1E 1740.7–2942 to the Free Spheroidal Model does not significantly improve the fit. The 95% confidence upper limit to time-averaged narrow 511 keV line emission from 1E 1740.7–2942 for this model is $6 \times 10^{-5}\ \gamma\ cm^{-2}\ s^{-1}$. This model-dependent limit
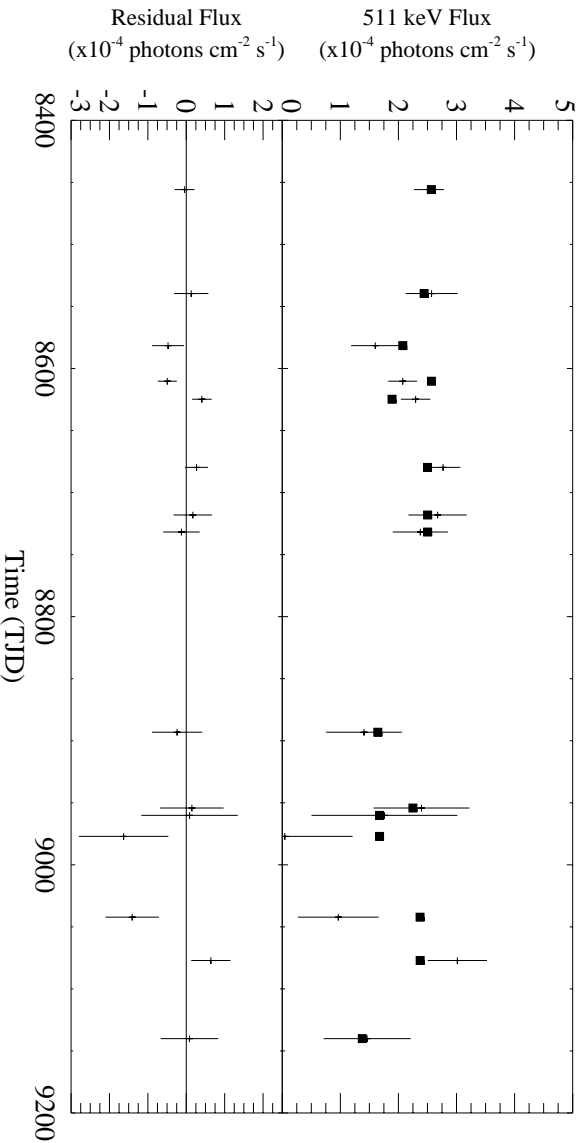
Figure 2: Averaged narrow 511 keV line flux from the OSSE observations within $\sim 1°$ of the Galactic center. The squares indicate the expected fluxes for the best-fit Free Spheroidal Model.

represents the value of the point-source flux at $\chi^2_{min} + 3.8$ for fits with all of the Free Spheroidal Model parameters free. This is nearly an order of magnitude lower than the limits imposed by the SIGMA and GRIP instruments.

The best-fit Free Spheroidal Model can also be compared to historical observations by other instruments, as shown in Figure 3 where the estimated diffuse contribution has been subtracted from the reported flux for each observation. This figure indicates that the Free Spheroidal Model is an approximate description of the diffuse 511 keV line distribution, and suggests a historical limit to a time-variable component of the 511 keV line flux of $\sim 4 \times 10^{-4}$ γ cm^{-2} s^{-1}.

CONCLUSIONS

The disk and spheroid components of the Galactic 511 keV line distribution may represent two different sources of positron production. A large fraction of the disk emission, with a 511 keV line flux of $\sim (3-5) \times 10^{-4}$ γ cm^{-2} s^{-1} from the inner radian of the Galaxy, is probably due to the radioactive decay of ^{26}Al. Radioactive ^{26}Al is unstable to β^+-decay (82%) and feeds the first excited state of ^{26}Mg (99.8%), resulting in the emission of a 1.809 MeV photon. The 1.809 MeV line has an observed flux of $(3.5^{+0.8}_{-1.3}) \times 10^{-4}$ γ cm^{-2} s^{-1} from the inner radian of the Galaxy (Harris *et al.* 1990), with a distribution which is somewhat clumpy and is extended along the Galactic plane over a longitude range of $-35° - 40°$ (Diehl *et al.* 1994). Assuming both the positrons and ^{26}Al in the interstellar medium are in equilibrium and a positronium fraction of ~ 0.9, the expected 511 keV line flux due to positrons produced by ^{26}Al decay is $(1.9^{+0.4}_{-0.7}) \times 10^{-4}$ γ cm^{-2} s^{-1}. The distribution of this emission, which represents $\sim 40\% - 60\%$ of the estimated disk component, should roughly follow that of the observed ^{26}Al (it is interesting to note that the COMPTEL ^{26}Al observations suggest the central peak is located at a longitude of $\sim 2°$ (Diehl *et al.* 1994), which might explain the slight asymmetry in the 511 keV line distribution).

Residual Flux
(x10^{-4} photons cm^{-2} s^{-1})

511 keV Flux
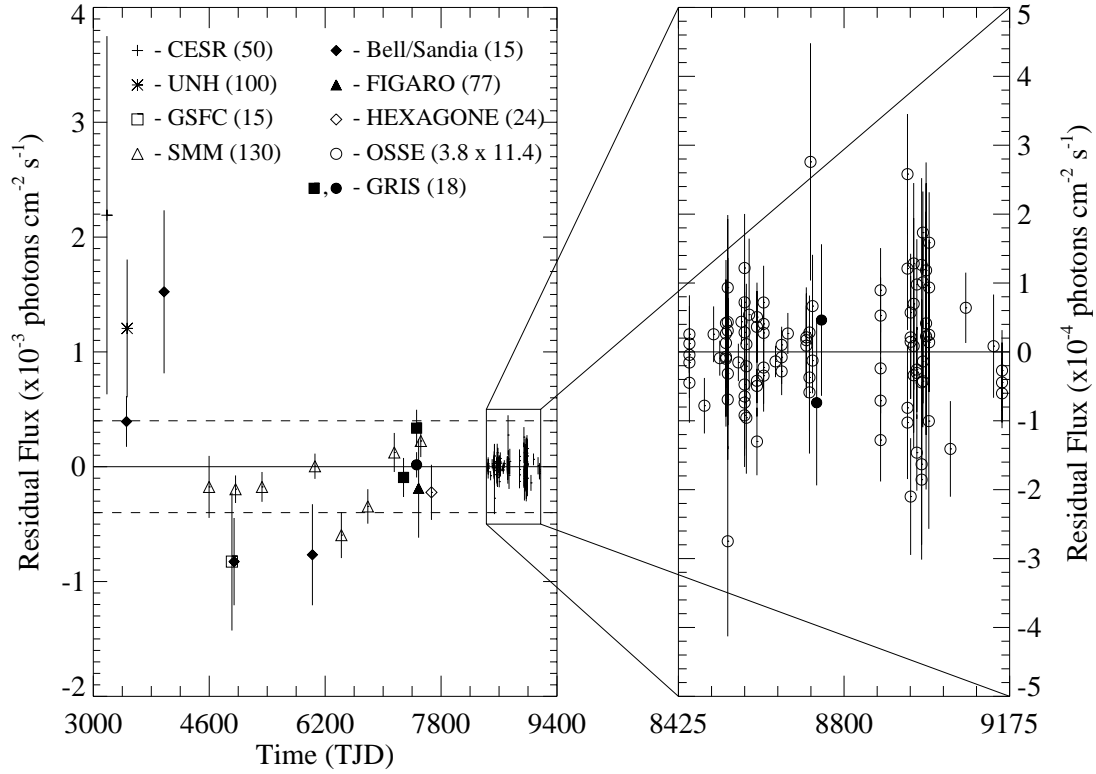(x10^{-4} photons cm^{-2} s^{-1})

Time (TJD)

Figure 3: The history of the 511 keV line flux from the Galactic center region as observed by various balloon and satellite instruments. Note that the uncertainties represent the statistical uncertainties only. The diffuse contribution for the best-fit Free Spheroidal Model has been subtracted from the reported flux for each observation. The model fit included all of the OSSE data and only the GRIS data points indicated by the filled circles. The numbers in parenthesis indicate the field-of-view of the instrument, in degrees. References: SMM – (Share *et al.* 1990); GRIS – (Gehrels *et al.* 1991; Leventhal *et al.* 1993); Bell/Sandia – (Leventhal *et al.* 1978, 1980, 1982, 1986); FIGARO – (Neil *et al.* 1990); HEXAGONE – (Chapuis *et al.* 1991); CESR – (Albernhe *et al.* 1981); UNH – (Gardner *et al.* 1982); GSFC – (Paciesas *et al.* 1982).

The remaining positrons are probably created by the decay of ^{56}Co and ^{44}Sc, which are thought to be produced primarily in Type Ia supernovae (Chan and Lingenfelter 1993). The 511 keV line flux for the spheroid component, $\sim 1.7 \times 10^{-3}$ γ cm^{-2} s^{-1}, corresponds to a positron production rate of $\sim 7 \times 10^{42}$ positrons s^{-1} assuming the positrons are in equilibrium. If the positrons are primarily produced by the decay of ^{56}Co and ^{44}Sc, this positron production rate implies a limit to the present rate of Galactic iron nucleosynthesis of ~ 0.7 M$_\odot$ per 100 years (see Ramaty, Skibo & Lingenfelter 1994 and references therein). A better determination of the distribution of the 511 keV line emission will provide more significant constraints on the positron production rate for the disk and spheroidal components, and on the present rate of Galactic nucleosynthesis of β^+-unstable nuclei.

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